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THE RELATION OF ROOF SIZE TO TEMPERATURES OF IRRADIATED METAL ROOF SECTIONS EXPOSED TO FORCED CONVECTION

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CONTENTS

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THE RELATION OF ROOF SIZE TO TEMPERATURES OF IRRADIATED METAL ROOF SECTIONS EXPOSED TO FORCED CONVECTION

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INTRODUCTION

In 1958 and 1959, a study was made to determine the suitability of thermal models for comparing radiant heat loads in semi-enclosed livestock housing (6).[4] Measurements showed that the surface temperatures of equally exposed roofs on the models varied with roof size. This phenomenon is neither mentioned nor explained in the literature, though it could influence the design of roofs significantly. These temperature differences, and their cause, were investigated under field and laboratory conditions. The initial results are presented in this publication.

TEMPERATURES OF THERMAL MODEL ROOFS, 1958

In 1958, the radiant heat loads in a standard 8' x 12' hog shelter were compared with the radiant heat loads in two models of this structure, one about $\frac{1}{2}$-scale and the other $\frac{1}{4}$-scale (fig. 1). Interior surface temperatures of these buildings were measured with thermocouples at the center of each surface. The center roof temperatures of the three shelters were very different, even though the roofs were identical except for size. Maximum roof temperature differences of 20 °F. were not uncommon during periods of peak air temperatures. The factor of major importance, however, was that the centerpoint temperature of the full-scale roof was highest in nearly all cases, with the $\frac{1}{2}$-scale and $\frac{1}{4}$-scale roof temperatures being lower in that order.[5] The variations in temperature are illustrated in figure 2, which shows the centerpoint temperatures for the three roofs as functions of air temperature. Point scatter around each regression curve was attributed primarily to fluctuating solar irradiation, wind velocity, and wind direction. Correlation between roof centerpoint temperature and air temperature was poor for the full-scale shelter and fair for the models, the correlation being for the full-scale, 0.377; for the $\frac{1}{2}$-scale, 0.784; and for the $\frac{1}{4}$-scale, 0.886.

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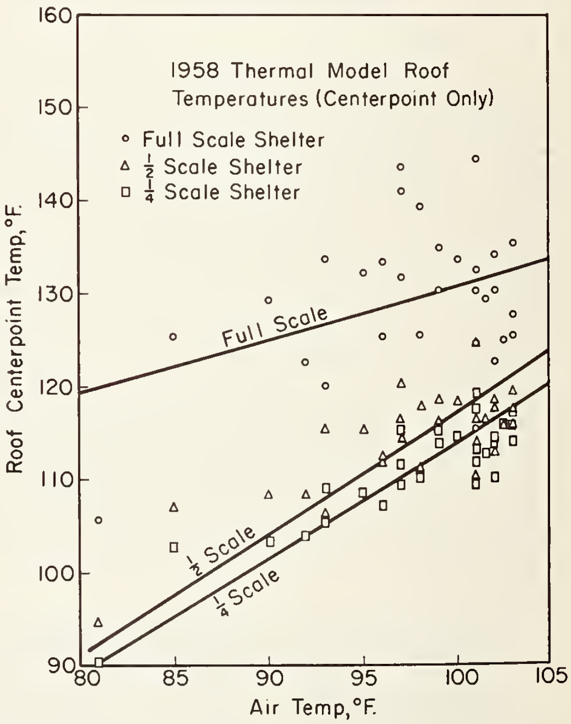
[4] Numbers in parentheses refer to references at end of this report.
[5] Roofs of all three test structures were constructed of 0.019" mill-finish corrugated aluminum (single thickness, uninsulated) nailed to wooden purlins. Actual roof sizes of the structures were as follows: Full-scale, 8' 8" x 13' 6-1/2"; $\frac{1}{2}$-scale, 3' 9-3/4" x 5' 9-3/4"; $\frac{1}{4}$-scale, 2' 1-7/8" x 3' 3-1/8".

Figure 1.--Scale models and prototype hog shelter during comparisons of radiant heat loads and surface temperatures.

Figure 2.--Roof temperatures recorded at the centerpoint as a function of air temperature for model hog shelters.



TEMPERATURES OF FLAT METAL PLATES, 1959

Further extensive field study was made in 1959 with 22-gage flat galvanized steel plates of three sizes, 4' x 6', 2' x 3', and 1' x 1-1/2'. The plates were mounted on 4-foot-high wooden frames (fig. 3). Thermocouples were attached to measure the undersurface temperature at intervals along the diagonals of each plate.

Plate size affected surface temperature not only at the centerpoint but over the entire plate surface (5). The centerpoint temperature was generally the highest measured surface temperature on each plate. Similar to the thermal model studies, the largest surface (4' x 6') had the highest temperatures and the smallest surface (1' x 1-1/2'), generally, the lowest.

The relation between centerpoint plate temperature and air temperature for each of the plates is shown in figure 4. The scatter can here also probably be ascribed to changing solar irradiation, wind velocity, and wind direction. The correlation between temperatures of the air and of the plate centerpoint was very good; 0.947 for the 4' x 6' plate, 0.960 for the 2' x 3' plate, and 0.964 for the 1' x 1-1/2' plate.

A multiple regression analysis was made, using the difference in temperature, in degrees F., between the plate centerpoint temperature and the air temperature as the dependent variable (Y). The three measured independent variables were: Air temperature, $^{\circ}$F. (X_1); wind speed, mph (X_2); and solar radiation as measured by an Eppley[6] pyroheliometer, Btu/hr-ft^2 (X_3). The regression equation for the 1' x 1-1/2' plate was

$$Y = 5.38 + 0.08X_1 - 1.25X_2 + 0.037X_3.$$

This equation indicates an air temperature change to result in an almost equal variation in plate temperature; the air velocity term is also of major importance. Solar radiation, while indicated to have a lesser effect on the variation of the plate-air temperature difference, is of considerable importance as a direct cause of increased temperature of plates exposed to the sun. This has been demonstrated by a comparison of unpainted and white-painted galvanized steel sheets (1); the white-painted were as much as 50° F. cooler than the unpainted.

[6] Mention of products in this paper does not constitute an endorsement by the U.S. Department of Agriculture over similar products which are not mentioned.

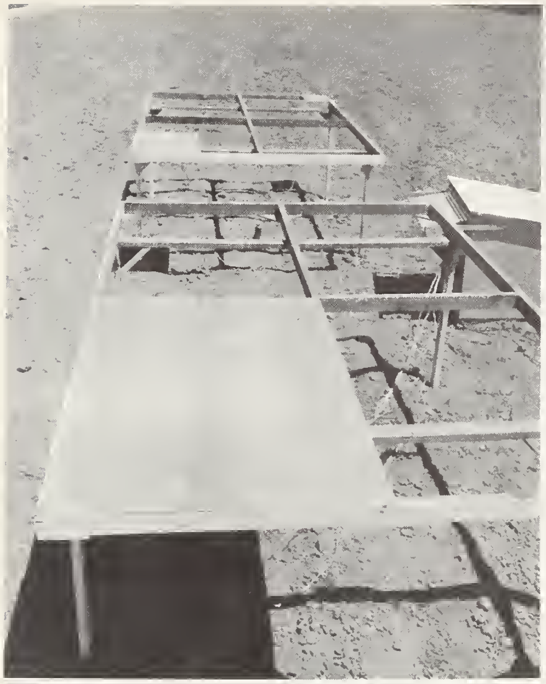


Figure 3.--Three-sized plates in place on testing frames located in a relatively open area of a plowed field. The longer plate dimensions are oriented east-west.

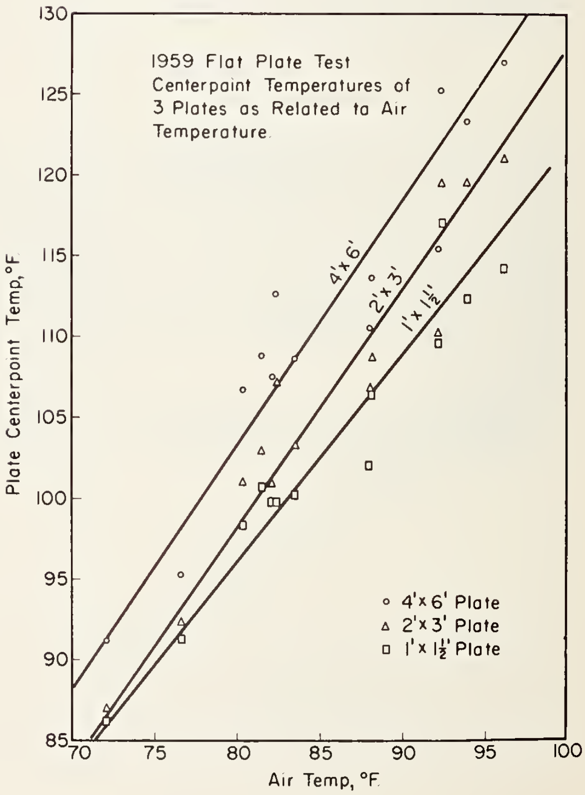


Figure 4.--Plate centerpoint temperatures as a function of air temperature for three-sized plates.

LABORATORY INVESTIGATIONS OF FLAT-METAL-PLATE TEMPERATURES, 1960-61

Test Equipment and Procedures

Roof surface temperatures in both the model study and the field study of flat-plate temperatures were complicated by the uncontrolled factors of solar irradiation, wind velocity, and wind direction. To control as many of these as possible, study with flat metal plates was continued in the laboratory. A low-speed induced-draft wind tunnel was used, with provisions for imposing a uniform irradiation level over the floor of the test section. The test section was 5 feet long, with the leading edge 13' 6" from the tunnel inlet. Total length from air inlet to outlet was 27' 4". The dimensions of the tunnel interior were 27-3/4" x 27-3/4" along the entire length up to the fan unit, giving a cross-sectional area of 5.35 square feet. The 36" propeller-fan unit was connected to a variable-drive electric motor to obtain air velocities covering the range of 1-1/2 to 10 mph. Figure 5 shows a view of the wind tunnel.

Solar irradiation was simulated in the test section by a battery of fifty 125-watt industrial infrared heat lamps, controlled by variacs. (See fig. 6.) These lamps were installed above a section of diffuser glass to irradiate the test section.

Velocity profiles near the upstream and downstream ends of the test section showed the pattern of velocities across the tunnel breadth to be quite uniform for a distance of 10 feet on each side of the centerline. Gravel barrier "turbulence stimulators" near the tunnel air inlet, together with the tunnel length ahead of the test section, provided a minimum turbulent layer 4.6 feet in depth (calculated) on the test section floor when the mainstream air velocity was highest, 890 fpm. The gravel barrier also tended to produce a more uniform velocity distribution in the vertical plane of the test section. The variation in transverse velocity distributions along the length of the test section was significant.

Details are given elsewhere (4) on wind-tunnel calibration for uniformity of airflow, mainstream air velocities (U_m)[7] for various fan speeds, and uniformity of irradiation over the test section. On the basis of this calibration, maximum roofing plate dimensions for temperature determinations were no greater than 18" x 48". Because the plates were mounted on a stack of insulation boards on the tunnel floor, the upper plate surface was within a layer of turbulent flowing air simulating exposure to natural atmospheric surface winds. Such mounting also allowed simulation of airflow over and around the sides and roof of a structure.

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[7] The mainstream air velocity is the average velocity of the air flowing through the tunnel, as determined by traversing the tunnel cross section by means of the method outlined by Ower (7, ch. V).

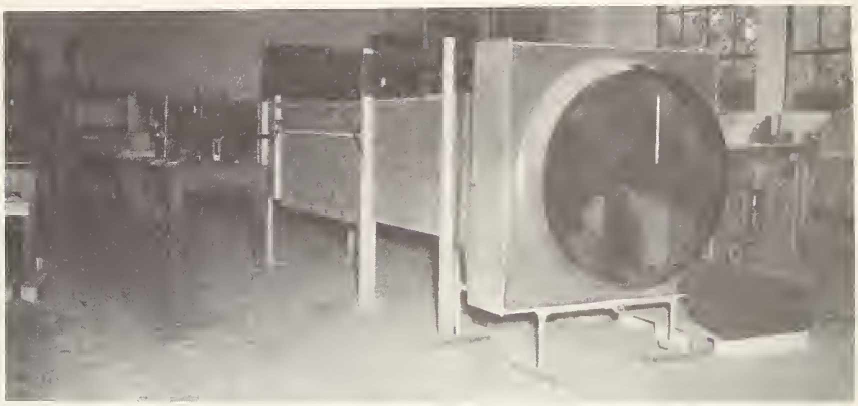


Figure 5.--Wind tunnel unit in test room; propeller fan powered by variable-drive motor unit.

Figure 6.--Closeup of tunnel test section, showing access door and radiant heat source (one reflector wall of lamp enclosure removed). Lamps irradiate floor of test section through diffuser glass which forms top of test section.

Irradiation was controlled at the mean levels listed below for the four mainstream air velocities used in the test:

Mainstream air velocity (U_m)	Irradiation level[1]	Max. variation of irradiation about mean
F.p.m.	Btu/hr-ft^2	%
140	410	±4.3
220	402	±4.5
445	379	±4.6
890	335	±3.7

[1] Irradiation produced by the lamps was constant throughout the test; the decrease in irradiation level was due to the cooling of the interior tunnel surfaces with increased airflow. The cooler surfaces radiated less energy.

Approximate percentages of irradiation in the short-wave range (below 4 microns wavelength) and in the long-wave range (above 4 microns) were determined from simultaneous readings with a total hemispherical radiometer and an Eppley[8] pyroheliometer. About one-third (35.4%) of the irradiation striking a test plate was short-wave. The remainder was long-wave energy emitted by the lamps and by various tunnel surfaces heated by direct and reflected energy from the lamps. By comparison, irradiation provided by the sun and sky in the previously mentioned field study was in reverse proportions--approximately two-thirds was short-wave.

Test plates of several lengths and widths were cut from a sheet of new 22-gage flat galvanized steel. Thermocouples were placed along the centerline on the undersurface of each plate and at points located to provide the desired surface temperature pattern. Each test plate was placed on an insulation-board stack, 2-1/2 inches high, whose dimensions conformed to those of the plate, and then subjected to the turbulent airflow and uniform irradiation. Surface temperatures were then recorded. The leading edge of each plate was perpendicular to the direction of the airflow.

Results and Discussion

In analyzing the results, the mainstream air temperature, t_∞, was subtracted from the plate surface temperature, t_w, to obtain the air-surface temperature difference, Δt. This eliminates air temperature as a variable, leaving the air-surface temperature difference dependent on the controlled variables of plate length (L), plate width (W), and the combined effects of mainstream air velocity (U_m) and irradiation level.

Figure 7 shows the effect of plate length on air-surface temperature differences (Δt) along the centerline of plates 18 inches wide. The manner in which these temperature differences change along the plate length (in the direction of airflow) is qualitatively as expected, and can be interpreted in terms of

[8] See footnote 6.

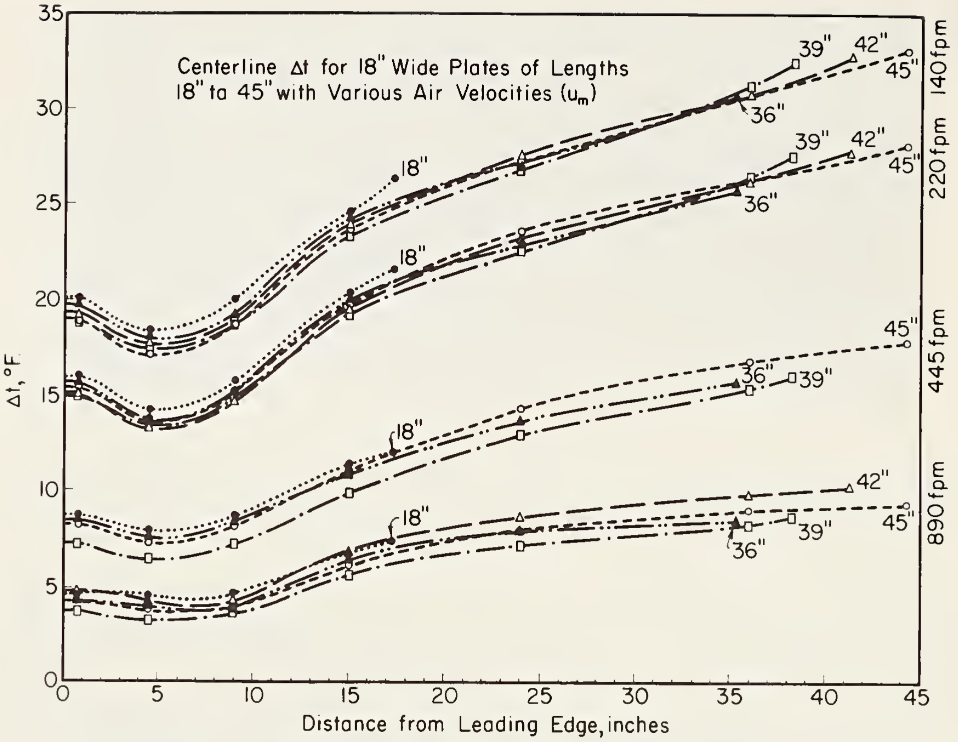
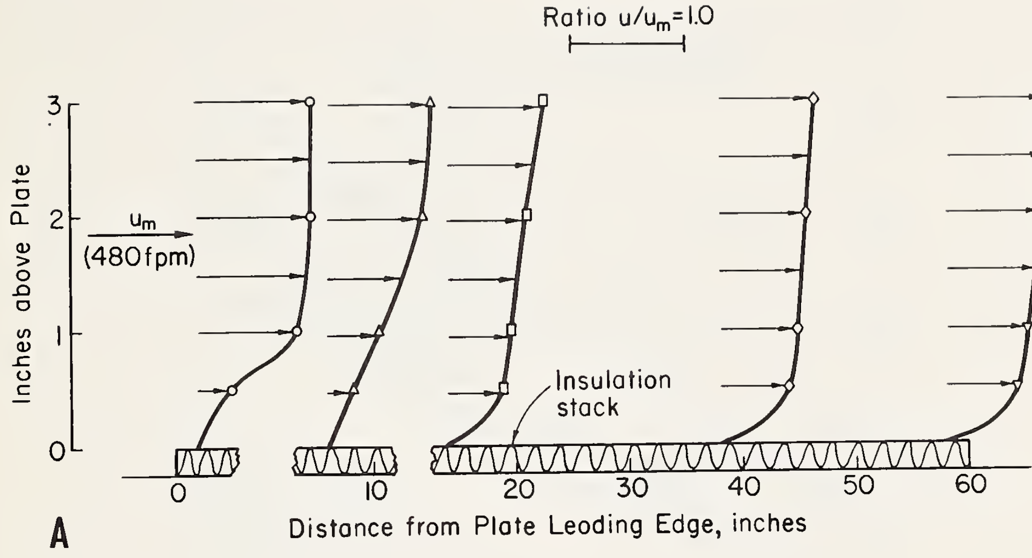


Figure 7.--Effect of plate length on air-surface temperature differences along the centerline downstream from the plate leading edge (for four air velocities).

boundary-layer theory.[9] A thermal boundary layer exists in addition to the momentum boundary layer when the plate temperature, t_w, and free stream temperature, t_∞, are not equal (as in the case of the roof temperatures studied). For air flowing over a plate, the thermal and momentum boundary layers can satisfactorily be considered the same (i.e., of equal depths at a given distance downstream from the leading edge) (3, p. 143). Thus, velocity profiles at various points along the plate (fig. 8, A) provide an indication of the temperature profiles. Near the leading edge, the velocity gradients within the boundary layer are extremely large. In the immediate vicinity of the edge, the gradients might be negative, indicating an eddying or "dead spot" area. This area will act as an insulating barrier to heat removal, resulting in relatively high air-surface temperature differences. Downstream from this region, however, a normal boundary-layer buildup should occur, as is shown in figure 8, B. The heat lost by convection will depend on the thickness of this boundary layer (thicker boundary layer results in less convection heat transfer). Thus, the air-surface temperature differences should increase with increasing distance downstream.

In summary, then, the following temperature pattern along the plate should be expected: In the immediate vicinity of the leading edge, where a stagnation region exists, the air-surface temperature difference should be relatively high. The temperature difference will drop off as the boundary-layer phenomenon takes over; the difference will increase as the plate length is traversed. Figures 7 and 8 illustrate the agreement in the surface-temperature and boundary-layer

[9] At the surface of the plate, the velocity of fluid flow is zero; the velocity at a very small distance from the surface is close to the mainstream velocity, u_m. This very thin layer of fluid containing large velocity gradients, called the momemtum boundary layer, starts from zero thickness at the leading edge of the plate. For practical purposes, the upper limit of the boundary layer is defined as the location where the velocity is 99% of the mainstream velocity.



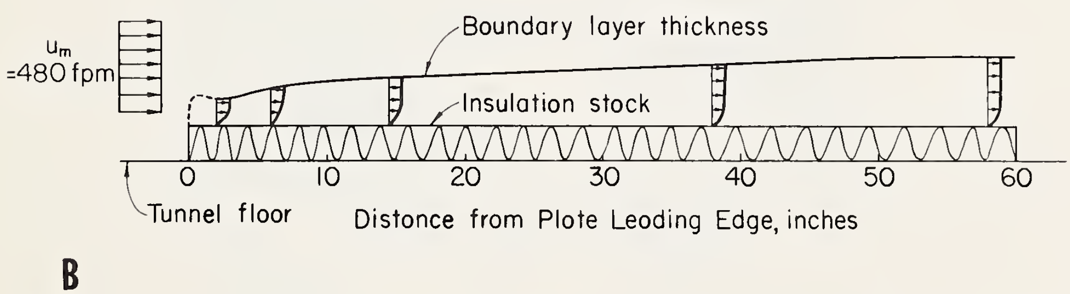


Figure 8.--A, Velocity profiles above the surface of a simulated test plate at selected distances downstream from the leading edge.

B, Boundary-layer buildup over the simulated test plate, approximated from the velocity profile data.

buildup patterns. Also, since the boundary-layer thickness will decrease with increased velocity, the air-surface temperature difference will decrease. Figure 7 shows this to be the case.

The boundary-layer buildup explains the measured temperature variation with plate size in the field studies. When a plate is subjected to a given radiant energy, air temperature, and air velocity, the center temperature of that plate should be a function of the distance from the center to the leading edge of the plate.

The effect of plate width on temperature differences between the plate and air along the centerline of plates 30 inches long is shown in figure 9. At each air velocity, a change in plate width caused slight variation in the pattern of temperature differences. This was probably caused by the interaction of boundary layers building up simultaneously from the sides and from the leading edge of the plates, as discussed by Elder (2).

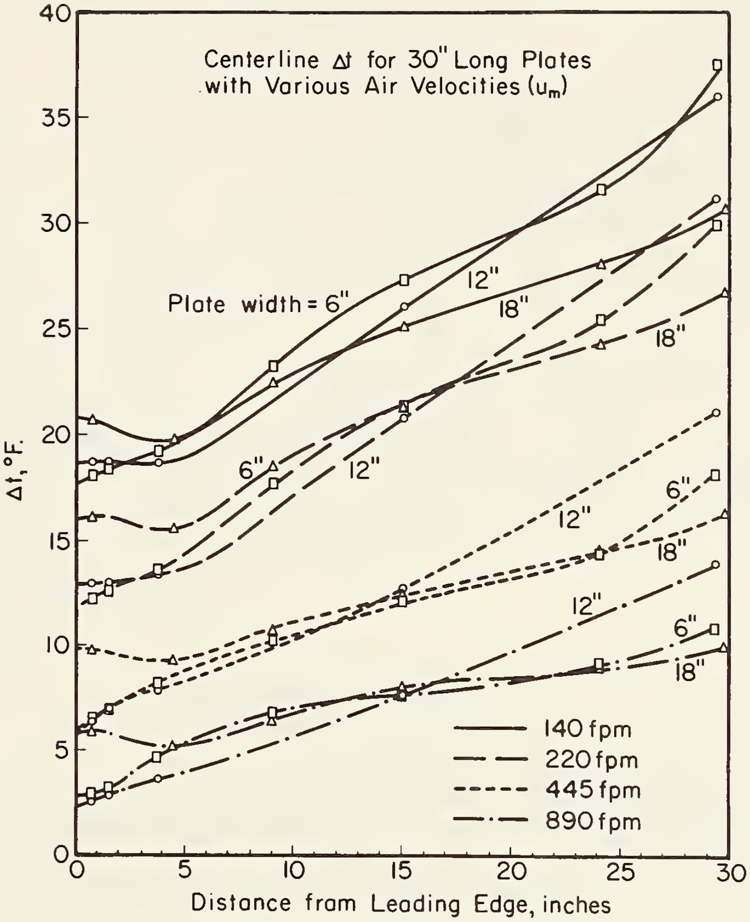


Figure 9.--Effect of plate width on air-surface temperature differences along the centerline of 30-inch-long plates (for four air velocities).

Air-surface temperature differences of plates 18 inches wide were quite uniform across the width of the plate, especially at distances of 4-$\frac{1}{2}$ inches and more downstream from the leading edge. This was not as true for the narrower plates with the widths of 6 and 12 inches. Most, if not all, of the nonuniformity is undoubtedly due to boundary-later interaction, previously mentioned.

To aid visualization of air-surface temperature differences over the entire plate, isometric drawings of the temperature "surface" over a plate of each width are shown in figure 10, for a mainstream air velocity of 140 fpm. These drawings show quite well the good uniformity in the case of the 18-inch-wide plate and the tendency toward nonuniformity with a decreasing plate width.

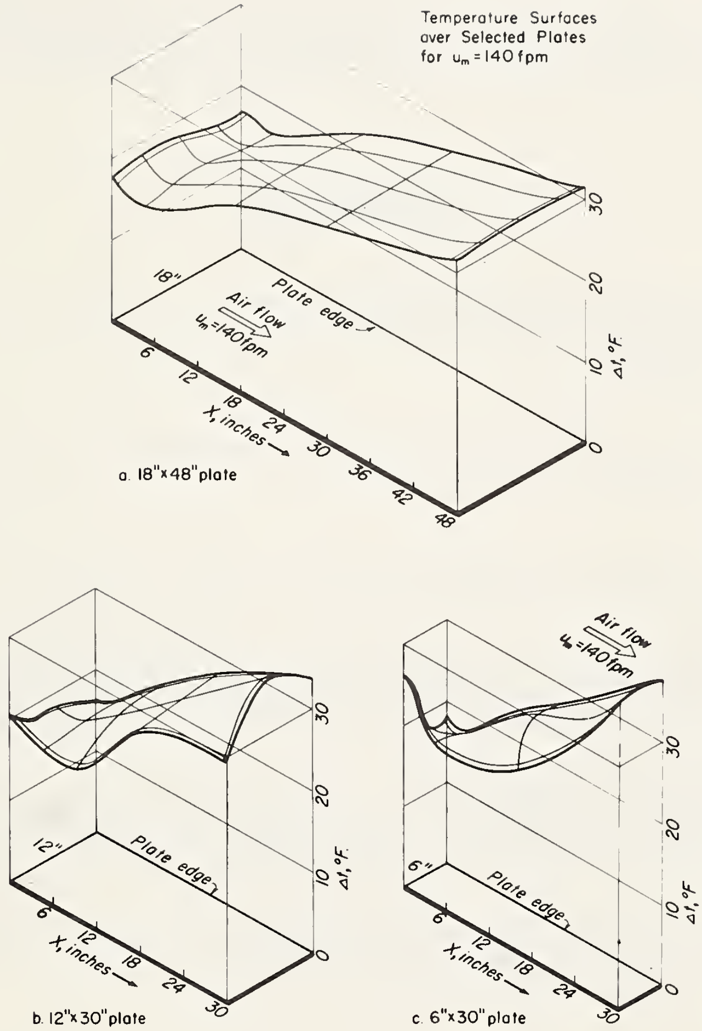


Figure 10.--Isometric views of "surfaces" of the air-surface temperature differences over three selected plates for a mainstream velocity of 140 fpm.

SUMMARY

Results of two field investigations concerning variations of metal roof surface temperatures with differences in roof size are presented. Results from a laboratory study in a low-speed wind tunnel show agreement with the field studies as to increased temperature of plate centerpoint with an increase in plate size. The laboratory study also showed this effect to be due to various stages of the

buildup of the boundary layer over the plate (roof section), depending on plate size. The close relation found between airflow over the plate and the surface-temperature patterns of the plate establishes the importance of convective cooling of roofs.

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